Chapter 27
LCA of Electromobility

Felipe Cerdas, Patricia Egede and Christoph Herrmann

Abstract Private transportation is increasingly responsible for a significant share of GHG emissions. In this context, electric vehicles (EVs) are considered to be a key technology to reduce the environmental impact caused by the mobility sector. While EVs do offer an opportunity to decrease the production of greenhouse gases radically by avoiding the generation of tailpipe emissions, different technological challenges must be overcome. On the one side, the production of the battery system is of significant importance as it is reckoned to be responsible for around 40–50% of the total CO_2-eq. emissions of the vehicle's manufacturing stage. Moreover, the additional requirements for metals like copper and aluminium for the battery system as well as rare earth metals for the production of electric motors might lead to shifting the problem to other life cycle stages or areas of impact. On the other side, the source of the energy used to power an EV has an ultimate influence on the environmental impact caused during the vehicle's use stage. The life cycle assessment methodology is normally used to measure the environmental impact of electric vehicles and to identify potential problem shifting. In this chapter, we present an overview of the application of the methodology within the electric mobility sector.

27.1 Introduction

27.1.1 Current Context

Transportation poses great challenges for the sustainability agendas of countries worldwide. As reported in the latest climate change report by the IPCC, by 2010 direct anthropogenic greenhouse gas (GHG) emissions from the transportation

F. Cerdas (✉) · P. Egede · C. Herrmann
Chair of Sustainable Manufacturing and Life Cycle Engineering,
Institute for Machine Tools and Production Technology, Technische Universität Braunschweig, Langer Kamp 19b, Brunswick, Germany
e-mail: juan.cerdas-marin@tu-braunschweig.de

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sector increased from 2.8 Gt CO_2-eq. in 1970 to 7.08 Gt CO_2-eq. (Sims et al. 2014). In that year, this sector contributed to up to 23% of the total energy related CO_2 emissions (Sims et al. 2014). In addition, individual transportation ownership is projected to grow up to 2 billion vehicles by 2050 (IEA 2009) reaching rates of 12 Gt CO_2-eq./year (Sims et al. 2014). The transition towards a more sustainable individual transportation urges for radical changes regarding transportation means, fuel consumption and resulting GHG emissions. In this regard, different strategies have emerged worldwide, including:

- The development of alternative fuels (e.g. biofuels see Chap. 30).
- The reduction of driving distances by facilitating other modes of commuting, improving public transportation or its accessibility, promoting car sharing programs, among many others.
- The optimisation of existing technologies (or the development of new ones) to increase the vehicle's energy efficiency. For instance, by improving the efficiency of the drive train.
- The reduction of the vehicle's weight by substituting materials and implementing new design concepts or modern production technologies (e.g. 3D printing).
- The development of alternative powertrains such as electric vehicles together with increased production of renewable energy.

Regarding the latter, electric vehicles (EVs[1]) are seen by many countries as a promising technology to achieve significant reductions of GHG emissions. In Germany, for example, the national electric mobility plan disclosed a set of ambitious objectives which among others include the mass scale production of lithium-ion batteries, as well as the production of battery and plug-in hybrid electric vehicles (BEV and PHEV) to ultimately place 1 million electric vehicles on the country's roads by 2020 (German Federal Government 2009). Moreover, in countries like Sweden and the United States, market sales shares of EVs reached in 2014 over 1%[2] (OECD/IEA 2015).

The successful penetration of Electric Vehicles (EVs) in the automotive market depends on three key factors, i.e. costs, customer satisfaction and engineering performance. In this regard, the environmental impact of an EV [or its potential reduction when compared to a conventional vehicle (CV[3])] plays an important role towards its market acceptance and is one of the main reasons for their development in the first place.

As they do not produce tailpipe emissions, EVs are believed to radically decrease greenhouse gas emissions. Yet, tailpipe emissions are only one aspect of

[1]We use the term EV to refer to battery electric vehicles (BEV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV).

[2]In Norway, the EV market share represents more than 12% and in the Netherlands more than 3%.

[3]In this chapter, we refer as conventional vehicles to vehicles powered with an internal combustion engine.

the analysis. The question of whether driving an EV is better than driving a conventional one from an environmental stand point, demands a more comprehensive analysis.

27.1.2 Technical Context of Electric Vehicles

The term electric vehicle EV refers to a vehicle that is fully or partially powered by electricity supplied by an electrochemical or electrostatic energy storage system and fully or partially propelled by an electric motor (Guzzella and Sciarretta 2005). In this chapter, we classify electric vehicles into battery electric vehicles (BEV) and hybrid electric vehicles[4] (HEV).

According to the degree of hybridisation, HEVs can be classified as mild and full HEVs. Figure 27.1 shows the configuration of the aforementioned types of EV and the respective flow and type of energy. EVs mostly use lithium-ion batteries the capacity of which varies depending on its size (see Fig. 27.1) and permanent magnet synchronous motors as traction motors. BEVs rely completely on electricity from the grid.

Broadly speaking, this electrical energy is converted by an electric motor into mechanical energy that is ultimately transmitted to the wheels. While its electrical range is larger than that of the other types of EVs, BEV depends almost completely on an on-board battery whose charging can take hours and thereby restrict its autonomy. Vehicles like the Nissan Leaf, the BMWi3 and the Tesla model S are some examples of mass produced BEV.

HEVs, in turn, depend on two different energy sources: fuel and electricity generated during regenerative breaking. Three types of HEV are distinguished according to how the energy flows between the vehicle's components. These include parallel HEV[5] (represented in Fig. 27.1), series HEV[6] and combined series–parallel HEV. Roughly, in an HEV the internal combustion engine (ICE) converts the fuel's chemical energy into mechanical energy, whereas the battery is charged internally through the energy produced by the electric motor/generator. Examples of mass produced hybrid vehicles are the Toyota Prius, the Ford Fusion and the VW Jetta hybrid.

Plug-in electric vehicles (PHEVs) are a type of HEV that can be plugged-in to be recharged from the electricity grid, providing the vehicle with an all-electric range

[4]The term "hybrid vehicle" is used to distinguish a car that combines an engine and an electric motor/generator (Guzzella and Sciarretta 2005).

[5]Parallel HEV: The energy flow follows two parallel routes: (i) The fuel tank feeds the internal combustion engine (ICE) which delivers mechanical energy to the wheels, (ii) the battery delivers electrical energy to an electric motor which delivers mechanical energy to the wheels.

[6]Series HEV: The energy flow follows a single route. The fuel tank feeds an ICE that is couple to a generator. The generator charges the battery which provides electrical energy to an electric motor. The electric motor delivers mechanical energy to the wheels.

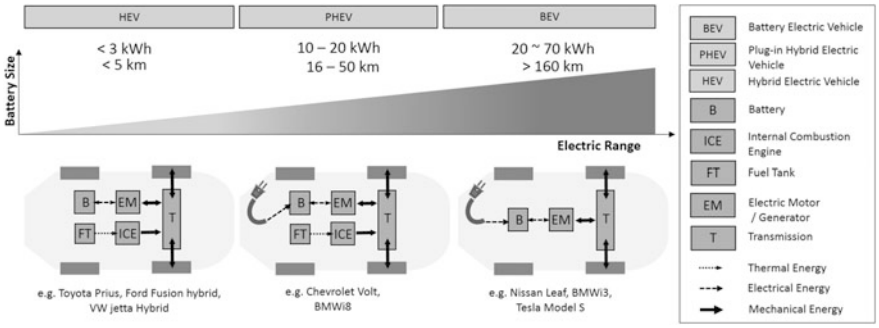


Fig. 27.1 Technical characteristics of electric vehicles

that is usually enough for a daily urban utilisation.[7] In the case of a PHEV, the ICE works as a range extender. Examples of mass produced PHEVs are the Chevrolet Volt and the BMW i8. A more detailed description of the EV's main components that should be considered for an LCA is presented in Sect. 27.2.2. For more general information regarding technical characteristics of electric vehicles, their components and their well to wheel (WTW—see Fig. 27.2) energy efficiency, we refer the reader to the work of Helmers and Marx (2012) and Yong et al. (2015).

27.1.3 Role of LCA in the (Electric) Mobility Sector

Imagine for example that we are interested in comparing the environmental impact of driving 100 km at a fixed speed, with a Land Rover Discovery V6 against a Suzuki Alto 1.1 both conventional gasoline-engine-driven vehicles. This example is naturally very trivial one could easily argue that the heavier the car is, the more energy is required to move it, and therefore the larger its fuel consumption and thus its carbon footprint. The environmental impact of a CV is driven by how much fuel is used and how efficiently it is combusted during its operation. In this sense, a common practice is to compare the potential environmental benefits of two or more fuel combustion technologies by framing the study on a well to wheel (WTW) approach. As represented in Fig. 27.2, the WTW analysis is focused on assessing the life cycle environmental impact of the energy carrier used to power a vehicle (e.g. liquid fuel, natural gas, hydrogen and electricity).

This approach is usually divided into well to tank (WTT) and tank to wheel (TTW) analysis. WTT analysis examines the upstream supply chain of an energy carrier, namely all the different conversion and distribution steps necessary to deliver energy to the vehicle. A TTW approach, contemplates exclusively the

[7]In the eLCAr guidelines, daily commuting in an urban environment is characterised by 40 km of driving range and a max speed of 160 km/h.

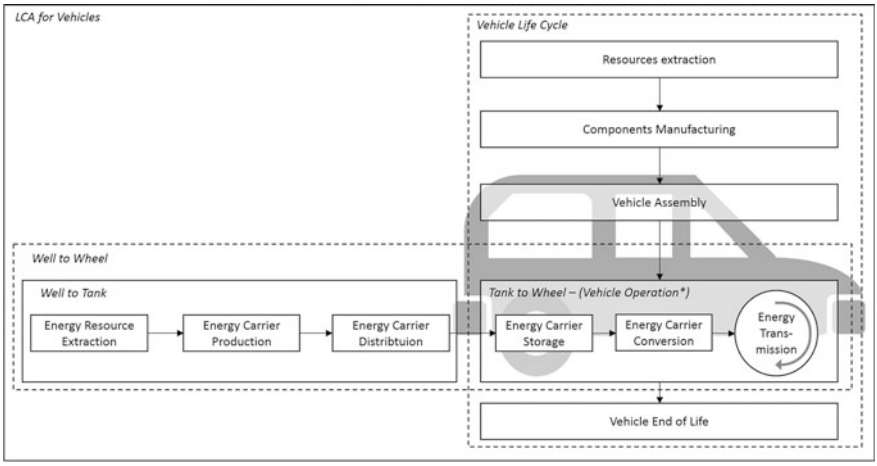


Fig. 27.2 Different perspectives for the environmental burden of vehicles. Adapted from Nordelöf et al. (2014)

efficiency with which the energy is converted by the engine and transmitted to the wheels. Here, the results are expressed in terms of the amount of tailpipe emissions per delivered traction or distance driven.

The example becomes less trivial if the analysis focuses on evaluating the impact associated with those strategies developed to reduce fuel consumption (e.g. through reducing the weight of the car) and tailpipe emissions (e.g. through developing alternative drive trains or non-fossil fuels). While the adoption of alternative lighter materials for the production of automotive components leads to a reduction of the overall vehicle's weight, the environmental consequences of such a measure require an analysis made with both eyes opened.

Compared to aluminium, a steering wheel made of magnesium can present GHG emission savings in the production stage if the magnesium is produced through an electrolysis process. When compared to an average magnesium Pidgeon process, the GHG emissions can be up to four times higher which leads to increase in GHG life cycle emissions (Ehrenberger 2013). Accordingly, if we consider the life cycle of the vehicle in our example, a measure to reduce weight through integrating magnesium intensively in the vehicle components may lead to an increase of the life cycle emissions.

In the case of an EV, the environmental trade-offs between materials, components, vehicle characteristics and specific factors influencing each of the life cycle stages are more complex to identify and to analyse.

To illustrate this case, consider the generic break-even analysis represented in Fig. 27.3. The graphic is divided in three parts including EV production, EV use stage and EV end-of-life as shown. Suppose now that we want to compare the environmental burden of driving a battery electric vehicle (BEV) against a CV. Disregarding the nature of the impact represented in the figure, before having driven

the first kilometre both cars are already responsible of a certain amount of impact U (U_{ev} for the EV and U_{cv} for the conventional vehicle). The environmental burden of the production stage of an EV is estimated to be larger than that of the conventional vehicle due mainly to the impact caused during the production of the battery pack.

Generally, a battery pack contains large amounts of aluminium and copper required as current collectors in the cells, as well as large quantities of other important metals that are necessary for the production of the electrode active materials (e.g. nickel, cobalt, manganese and lithium among many others) whose upstream supply chain in some cases includes significant mining processes characterised by being very energy- and SO_2 emission-intensive and in some cases producing significant amounts of toxic emissions. Furthermore, for the specific case of a BEV, the battery can represent up to 30% of the total vehicle's weight, a fact that has repercussions in the energy consumption of the vehicle in the use stage.

As both vehicles enter operation (see EV use stage in Fig. 27.3), their environmental impact is driven mainly by the fuel or energy demand. Given fixed conditions for the comparison (e.g. acceleration, speed, number of passengers, vehicle characteristics and driver behaviour), both vehicles are subject to basically the same nature of forces acting on them. Broadly speaking, these forces lead to a mechanical energy demand, mostly driven by the vehicle's weight that must be supplied to the vehicle's wheels.

The slope of the curves m represents the impact produced per kilometre driven. It is determined by (a) the total energy consumed by the vehicle including energy losses due to powertrain inefficiencies and the energy consumed by non-propulsion-related components; and (b) the impact produced due to maintenance and service. On a TTW perspective, not only is the conversion of energy and its transmission to the wheels much more efficient in a BEV, but also this process produces no tailpipe emissions at all. Nevertheless, from a WTW perspective, the environmental burden of both vehicle types will be different as the impact depends on the source (or mix of sources) of the energy carrier delivered to power the vehicle. In this regard, Fig. 27.3 presents three hypothetic scenarios for the vehicles under comparison: (BEV-1) EV powered with a moderate fossil energy mix, (BEV-2) EV powered with a large share of fossils within the energy mix and (BEV-3) EV powered with a low CO_2-eq. intensity energy mix. Important to notice here is that the sooner the EV breaks even, the larger is the potential reduction of its environmental burden in a life cycle perspective.

The right side of Fig. 27.3 (EV EoL) represents the end-of-life stage. The potential future reuse and/or remanufacture of components as well as the production of secondary material from spent automotive parts, implies the possibility of earning environmental credits which ultimately help reducing the overall life cycle impact.

As seen, the environmental impact of an EV can be influenced by many different factors making the range of results varying greatly from one scenario to another. LCA offers in this regard a straightforward methodology that not only enables a fair comparison between technologies, but also helps identify the many different

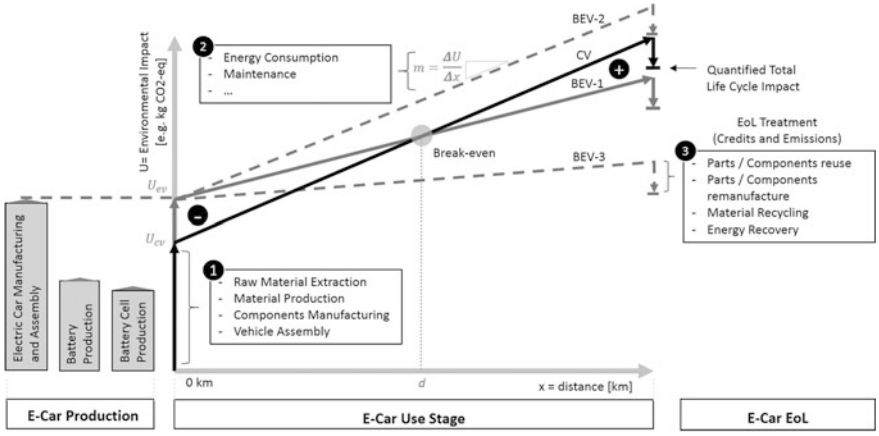


Fig. 27.3 Representation of a break-even analysis for the environmental burden of EVs (BEV-1, BEV-2 and BEV-3 represent electricity grid mixes causing moderate, high and low emissions of GHGs, respectively)

environmental trade-offs that can rise out of design strategies and transport policies. In short, LCA in the field of (electric)-mobility can be used to give well-grounded answers to the challenges:

- Comparisons between different types of EVs and CVs;
- The effect of the energy mix used to power vehicles;
- The effect of driving behaviour and local climate conditions (ambient temperature);
- The evaluation of weight reduction strategies;
- The analysis of the contribution of the traction battery to the overall environmental impact of an EV;
- The analysis of end-of-life scenarios mainly regarding the treatment of main components, especially batteries, electric motors and car body.

27.2 LCA of Electric Vehicles: Specific Methodological Issues

In this section, we introduce the reader to the application of LCA within the (electric)—mobility sector. To begin, a general overview of the application of the LCA methodology in the (electric)-mobility field is presented. Particularly, this section discusses issues of goal definition and problem scoping (see more about goal and scope definition in Chaps. 7 and 8) and gives a brief overview on data collection for the three major life cycle stages.

27.2.1 General Methodological Issues

EVs exist in several segments and configurations, each of which is composed by a specific set of components. These components are all responsible of a share of the total vehicle's environmental impact as they: (i) need to be produced, assembled and eventually disposed or recovered, (ii) may add additional weight to the vehicle which ultimately means energy consumption; and (iii) may affect the energy conversion efficiency thus increasing energy demand. In addition, due to the physical and technical interdependencies between components, a modification in one of them can lead to important changes in terms of design and/or performance in other components of the vehicle. This situation is particularly important to consider when defining the boundaries of the system and the modelling approach.

27.2.1.1 Definition of the Goal for the LCA of EVs

A comprehensive statement of the goal of the study may prevent an increase in the complexity of the analysis and reduce the degree of variability of the results (Nordelöf et al. 2014). Defining clearly and unambiguously the intended application of the expected results and the purpose of the study helps in general to identify and to describe the system that will best represent the product system.

For example, if the study is intended to make assertive comparisons about the environmental impact caused by driving an EV a certain distance using different types of batteries, the scope and inventory analysis of the study should explicitly contain information regarding battery characteristics, its energy density, weight and the potential interdependencies between components.

The reason for carrying out the study and the decision context also play an important role for the further definition of the product system and its boundaries. If an LCA aims to provide support during a decision making process, it is essential to consider all the potential effects of that specific decision. In this regard, framing the study within a decision context is important as it helps to define methodological and quality needs.

In line with the eLCAr guidelines (Del Duce et al. 2013) and the ILCD (European Commission—Joint Research Centre—Institute for Environment and Sustainability 2010), an LCA in the field of (electric)-mobility can be set in a situation context A (micro-level, product or process-related decision support) or B (meso-level and macro-level, strategic ("policy") decision support). Both contexts address potential consequences of a certain decision; however, the extent and nature are very different from each other (see more about decision context in Sect. 8.5.4).

These differences should be taken into account as they imply drastic changes regarding the way in which the involved supply chains are modelled. In general, an LCA intended to analyse short-term effects would most probably be best represented by situation A. This is for example the case where an LCA is performed on an operational level (e.g. comparison of two different brands of electric vehicles,

introduction of a new vehicle model or technology) and its modelling is based on current supply chains.

As there is a possibility that the market share of EVs strongly increases in the mid-term, large-scale consequences might occur on structures of adjacent systems linked to the product system being assessed. Some examples that can be identified in this regard are: i. the required infrastructure, ii. the production of electricity to meet the additional demand, iii. the rise of new material supply such as rare earth metals, lithium, copper and aluminium among other. An LCA that aims to address these circumstances is to be set in a situation context B. Comprehensive examples of goal and scope definition for the specific case of an electric vehicle are presented in the eLCAr guidelines.

27.2.1.2 Product System and System Boundary

In this section, we focus the analysis on a situation type A. The principal activities to be considered for an LCA of an EV are shown in Fig. 27.4. These can be grouped in four different stages: (i) The production of components which in turn comprises background activities located in the upstream supply chain (e.g. mining processes, production of materials and transportation among others). Although the battery is technically part of the drive train, we consider the battery system as an extra component. In that way, the component production activities are distributed in: (a) production of drive train, (b) battery and (c) car body; (ii) the vehicle assembly stage including, for example, the respective energy consumption, materials waste, painting processes and their emissions; (iii) the vehicle's use stage including charging patterns and driving behaviours, effect of local climate, production and distribution of energy, maintenance and service activities, and charging and road infrastructure; and (iv) the vehicle's end-of-life stage including credits for material and energy recovery from recycling, reuse and remanufacturing activities.

Notice that the boundaries are presented in a very general form. The actual system boundary should be described by tracking down the supply chain of the product system defined.

27.2.1.3 Functional Unit and Reference Flow

Finding an equivalent functionality for the comparison of EVs and conventional vehicles with an LCA can be very challenging. While the function can be expressed as a unit of service provided by the respective vehicle (e.g. a journey from point *A* to point *B*), it might be necessary to take a more descriptive approach so as to enable a fairer comparison and an easier interpretation of the results.

A more comprehensive picture of the systems being compared can be characterised by addressing questions such as how often, for how long, how well (or efficiently), under which conditions, among others.

As previously discussed, all the components of an EV have an influence on the energy demand during the use stage, which is mainly due to the weight added to the

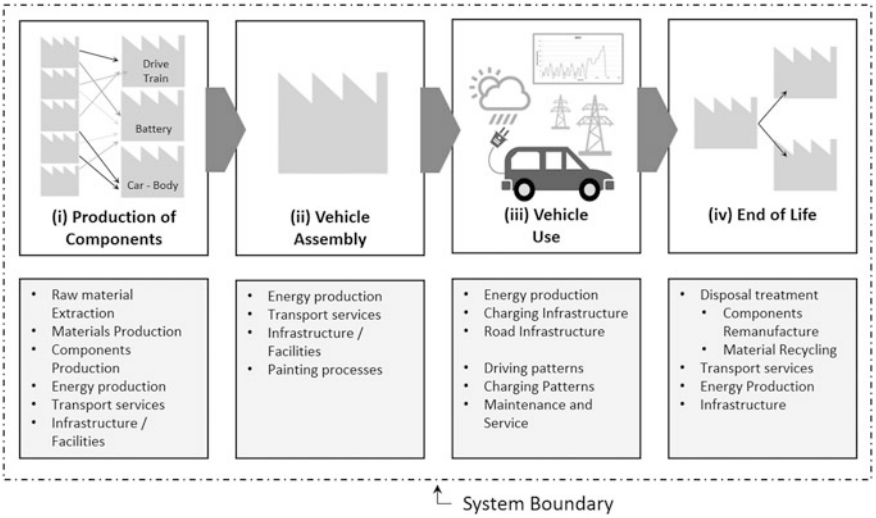


Fig. 27.4 Generic representation of the product system for the LCA of an EV

vehicle, but could also be related to issues of mechanical, electrical, thermal and electrochemical efficiency. This interdependency forces the LCA practitioner to consider a whole-vehicle perspective to approximate a description of an equivalent functionality.

EVs increase this complexity. On the one side, its efficiency is governed by properties such as ratio of discharge, energy density, number of cycles and by how the battery is used, but to add complexity, these properties differ from one battery system to another depending on both materials and production processes. On the other side, the mass added by the battery is responsible for a significant portion of the vehicle's energy demand during the use stage.

After overcoming this challenge, the vehicles under comparison are comprehensively defined in size and technical properties, and then a description of the conditions under which the vehicle is used should be given. This is particularly important for the case in which an LCA intends to compare an EV against a CV. As EVs have limited autonomy in terms of driving range and charging times compared to CVs, the functional unit should make reference to the type of application. These autonomy limitations are not relevant if the study aims to compare daily urban transportation as the technical requirements can easily be satisfied by the technologies being analysed. If instead the focus lies on analysing an average vehicle use, these mentioned limitations should be considered by for instance including a rented car or the use of public transportation to model the (long-)distance that the EV is not able to complete (Del Duce et al. 2013).

Another important aspect to consider is the variation of the overall vehicle efficiency from one to another driving cycle, which makes the LCA only valid for the driving cycle (or its mix) considered for the comparison. In brief, as described in

the eLCAr guidelines, the definition of the functional unit for an LCA in the field of (electric)-mobility can be formulated by describing parameters such as:

- Properties of the vehicle and/or its key components: vehicle class, weight, range per charge, lifetime, number of passengers per ride, maximum number of passengers among others.
- Interaction between the vehicle and its components and how this influences the unit of service.
- Location, time, geography, driving cycles, weather, etc.

27.2.2 Life Cycle Inventory Analysis in LCA of EV

While the definition of the goal and the respective decision context selected might limit the system to be studied, the analysis could take different focuses. For example, we may be interested in comparing the impact of two different battery configurations for a specific BEV. Although the battery of an EV could be modelled to a high extent independently from the vehicle, its weight might influence design considerations in other components that might end up adding more weight to the vehicle. This situation can lead to an increase of the upstream material supply chain and of course to more energy demand during the use stage of the vehicle. In such a system, disregarding the fact that the focus of the analysis lies on the battery system, the peripheral components affected shall be considered in the foreground system.

The interdependency matrix presented in the eLCAr guidelines[8] provides an overview of the most common interactions between components that might be taken into account. In this regard, the eLCAr guidelines distinguish two frequent situations in which an LCA may be focused. On the one hand, an LCA may be set to analyse one component. If the interaction between the component and the rest of the vehicle does not have a significant effect, the LCA can be restricted to the life cycle of that specific component placing it in the foreground system. If the component has an interaction with another vehicle component, then the foreground system of the LCA should include the entire vehicle, however, the level of detail of the analysis is not necessarily the same as for the component under study. On the other hand, the focus of the LCA may be on the complete vehicle, and in this case the foreground system should always include the whole vehicle.

A third situation can occur when, for example, the focus of the study lies in one of the product's life cycle stages. For instance, if the LCA aims to analyse the driving behaviours, geographic effects (i.e. climate, energy mixes, etc.) or business

[8]The interdependency matrix introduced in the eLCAr guidelines includes information on how one specific component might influence other components in an EV. These interdependencies are based on different assumptions including vehicle and driving characteristics. The interdependency matrix is available online.

models (e.g. car sharing or fleet application for example), the study might place the EV as being part of the background system. Once the foreground system is defined, the analysis focuses on identifying the data to be collected. We restrict this section to the description of the data collection process for the vehicle production stage, the estimation of the energy consumption during the use stage and the identification of unit processes to be modelled in the end-of-life.

27.2.2.1 Data Collection for the Vehicle Production Stage

A generic data collection plan for the vehicle production stage is presented in Fig. 27.5. The figure presents a simplification of the components to be considered as well as the processes and materials associated. Notice that the foreground system for the production stage of an EV is divided into production of components and vehicle assembly.

As recommended by the eLCAr guidelines, the production of each of the components in the foreground system should be subdivided into unit processes, which can be described as an independent operation and ultimately characterised in terms of their exchanges with the background system and the environment. In this regard, Fig. 27.5 includes a list of the most representative manufacturing processes used within the automotive industry as well as the main components that are recommended to be included.

Three groups of components are in focus: the glider, the drive train and the battery. Data collection in this field can be very exhaustive and time consuming. The eLCAr guidelines provide a rather general set of recommendations and only

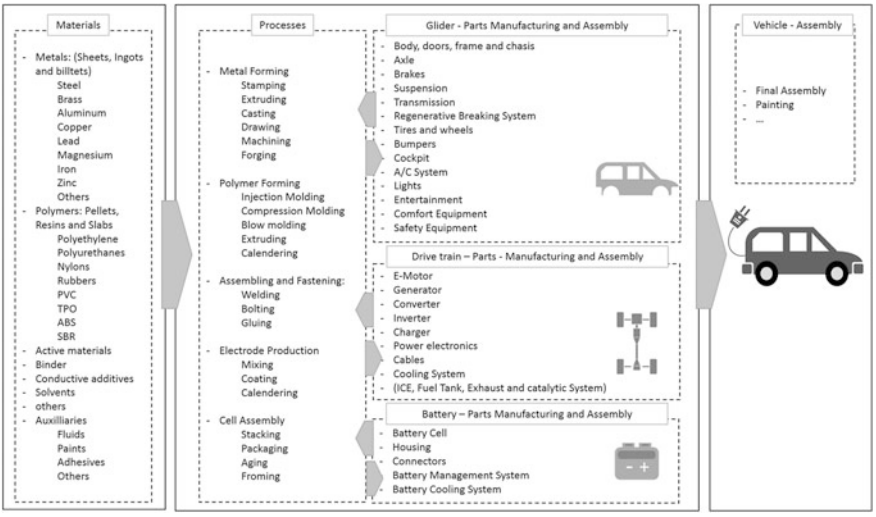


Fig. 27.5 Data collection plan for the production stage of EV

aim at pointing out the main issues to be addressed. In general, many LCAs done in the automotive industry are based on data modelled with the GREET model (Greenhouse gases, Regulated Emissions and Energy use in Transportation model) (Burnham et al. 2006).

The GREET model is an open source software originally created to evaluate vehicles on a WTW perspective. The current version includes a vehicle-cycle model, which contains information about the production and end-of-life stages of automotive components including alternative drive trains.

Furthermore, a common practice when modelling life cycle inventories of electric vehicles is to adapt or convert data from conventional vehicles (e.g. by replacing fuel tank with battery, combustion and exhaust systems with charging and power electronic systems). In this regard, the LCI of the VW Golf (Schweimer and Levin 2000) has often been adapted and extrapolated for research purposes. Moreover, detailed LCI for electric vehicles can be found in the research of Zackrisson et al. (2010), Hawkins et al. (2013) and Notter et al. (2010).

In addition, a few studies have published LCIs for the production of specific components. For example, the research by Majeau-Bettez et al. (2011), Ellingsen et al. (2014), Zackrisson et al. (2010) and Dunn et al. (2015) present detailed inventories for the production of traction batteries and research from Sullivan et al. (2013) offer models for the estimation of materials and energy used during the vehicles manufacturing and assembly stage.

27.2.2.2 Energy Consumption During the EV's Use Stage

The environmental impact of EVs during their use stage is influenced by different elements. Although the consideration of factors such as the charging and road infrastructure is also recommended, this section focuses on the estimation of the energy demand of the vehicle during its use (i.e. TTW in Fig. 27.2). For more information regarding the potential impact due to maintenance services and the generation of non-exhaust emissions, we refer the reader to the works of Del Duce et al. (2014) and Simons (2013).

The energy demanded by an EV to be included in an LCA can be measured or estimated. It can be divided into mechanical energy demand (i.e. the energy required to drive the vehicle from A to B), consumption of auxiliary devices, consumption due to air conditioning and heating requirements inside the vehicle, energy losses in the battery when the vehicle stays on standstill and the extra consumption of the battery due to charging losses.

The mechanical energy demand[9] of driving a vehicle over a certain distance is defined by the specific speed profile (v) of the trajectory and the power at the wheel

[9]The development of this section is based on the work done by Hofer (2014) and Guzzella and Sciarretta (2005).

(P_w) at every instant of the journey. P_w can be calculated by estimating the conservative and dissipative forces acting on a vehicle (Fig. 27.6).

The sum of all these forces is called traction force or force at the wheel (F_w) and is defined as:

$$F_w = F_a + F_r + F_g + F_k \tag{27.1}$$

Following, P_w can be defined as:

$$P_w = F_w \cdot v \tag{27.2}$$

Notice that P_w can be positive (i.e. the drive train needs to deliver torque to the wheels to propel the vehicle), negative (during braking) or zero (e.g. during coasting or when the vehicle is stopped). The mechanical energy demand can therefore be calculated by integrating P_w along a specific driving cycle.[10] The research from Hofer (2014) includes an estimation of the contribution of specific forces to the total mechanical energy demand of a vehicle for different driving cycles. Notice in Fig. 27.7 how for the same vehicle not only the total mechanical energy demand varies along the different driving cycles, but also the contribution of the different forces.

The electric passenger car transport and vehicle dataset developed for the ecoinvent v3 dataset (Del Duce et al. 2014) followed a similar approach. The energy consumption in the dataset is calculated based on the NEDC driving cycle with a power train efficiency of 70% and by increasing the efficiency by 5% for the parts where an urban-driving condition was modelled (i.e. therefore considering regenerative braking). The consumption of auxiliaries was estimated by Del Duce et al. (2014) assuming an average speed of 50 km/h and nominal powers of 3 kW

[10]A driving cycle is a description of a vehicle journey. It is usually represented by the variation of the speed against time on a specific road topography. Driving cycles are developed by executive/legislative bodies from different countries in order to standardise the measurement of the emissions produced and the consumption of fuel of a vehicle after a determined distance. Depending on the nature of speed changes (i.e. abrupt, gradual), driving cycles are divided into transient and steady state driving cycles. Transient driving cycles are those in which the speed changes constantly during the cycle. Examples of transient driving cycles are the New European Driving Cycle (NEDC) and the Worldwide harmonised Light vehicles Test Procedures (WLTP). The NEDC is supposed to represent the average usage of a passenger car in Europe and is composed of four urban cycles and one highway cycle. The WLTP is still under development but is based on statistical driving conditions from the EU, Japan, Korea, India and the US and is expected to replace the NEDC in the near future. Steady-state driving cycles basically represent a constant sequence of speed over time. For more information on driving cycles refer to Mock et al. (2013) and Barlow et al. (2009).

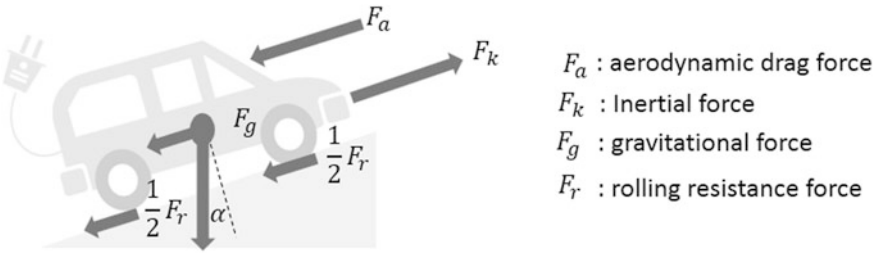


Fig. 27.6 Forces acting on a vehicle in movement. Based on Guzzella and Sciarretta (2005)

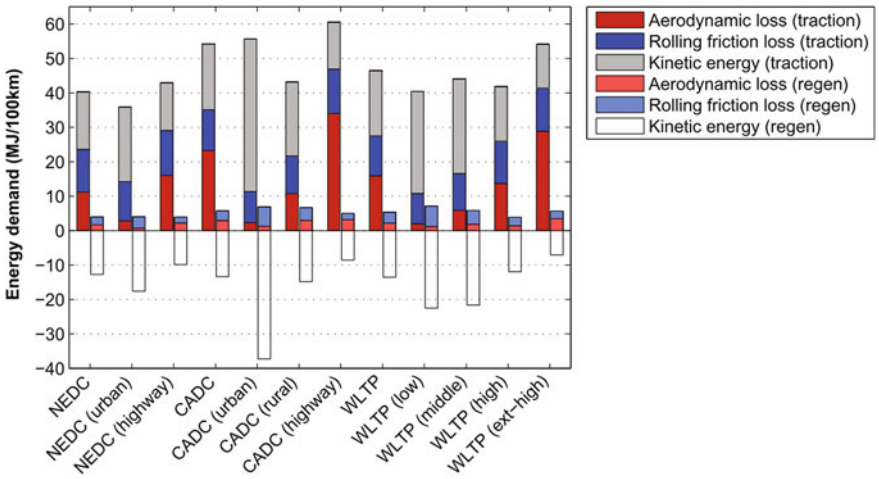


Fig. 27.7 Contributions to P_w for the NEDC and WLTP driving cycles. From Hofer (2014)

for heating, 0.6 kW for air conditioning and 0.5 kW for auxiliaries (i.e. radio, lights and so on). For every 100 km, a total of 2 kWh for the heating system and 0.4 kWh for the cooling system[11] were calculated.

From a WTT perspective, the energy mix dataset to be selected for the analysis will have a strong impact and shall therefore be carefully considered. Depending on the energy chosen mix, its contribution to the final results will vary among impact categories ranging from being negligible (e.g. when supplying energy from photovoltaic panels) to being the dominant hotspot (e.g. for the case of energy mixes with high shares of energy from coal power plants). Moreover, this mix can change in composition during the day or between seasons. In addition, as some regions are

[11]A more detailed approach for the estimation of the energy demand from auxiliaries and air conditioning systems can be found on the research from Egede (2016). More detailed calculations regarding energy losses on the battery system due to charging inefficiencies and to the discharging mechanisms while idling can be found in Del Duce et al. (2013).

interconnected, selecting energy mix datasets for specific places (e.g. countries) might mislead the interpretation of results. As recommended in the eLCAr guidelines, to enhance comparability the studies within the European Union should include in the analysis the European mix (EU-27).

27.2.2.3 Processes to Be Considered During the End-of-Life Stage of an EV

As recommended by the eLCAr guidelines, all the relevant processing steps involved after the use stage of an EV should be considered. First, the vehicle must be partly disassembled. This involves the treatment of specific hazardous materials (e.g. fluids, airbags, etc.) according to local regulations. Further components are recovered to be either recycled, remanufactured or disposed.

Of particular importance is the processing of the E-Motor and the battery system. Depending on the condition of the E-Motor, the motor can be remanufactured and therefore brought to a like-new condition to be reused. In this case, its life cycle should also be considered as it may be shorter than the motor's first cycle. If remanufacturing is not possible, the E-motor should be disassembled and its most important parts should be reused. Major processes for the treatment of the electric motor include the recycling of metals and the recovery of the permanent magnets and rare earth metals.

The end-of-life treatment of the traction battery should be considered within the system boundary. Modelling the recycling processes of a traction battery is difficult as they, being an emerging technology, are currently strongly under development. In other words, the LCA practitioner will have to deal with modelling a process that, partially or completely, does not exist. Nevertheless, as the topic of battery recycling becomes increasingly relevant due to environmental, economic and political reasons, future recovery of important metals such as aluminium, copper, nickel and cobalt is expected to contribute to the overall life cycle impact of an EV.

Current available research on battery recycling has identified several possible processing steps such as: battery dismantling down to the cell level and further processing of the cells. Since the battery dismantling process is mainly composed of mechanical steps, identifying the subprocesses and the material to be recovered is simple. However, the treatment of the cells might take several directions (e.g. hydrometallurgical and pyro-metallurgical processes) each of which involves technology-specific processes and thus differing from each other in terms of nature and amount of material recovered, processing costs (important to considered as it could indicate future market trends) and environmental impact.

27.3 Environmental Impact of EVs

While this field is still young, there is a relatively large amount of research trying to describe specifically the what, how and where of the interaction of electric vehicles and the environment. In the recent years, numerous LCA studies have been published not only in academic journals but also as environmental certifications from car manufacturers. Yet, results vary strongly between publications and benchmarking the results is a challenging exercise as most of the research available failed to express unambiguously the scope of the study and there are often inconsistencies in the application of the methodology. Moreover, lack of data and use of rough assumptions regarding energy consumption during the use stage, life time of the battery and inconsistencies on the selection of electricity mixes are common issues within the current research on LCA for EVs. Nevertheless, a few studies have provided very transparent life cycle inventories providing a more comprehensive understanding of the potential environmental impacts of electric vehicles.[12]

27.3.1 EVs Versus Conventional Vehicles

In this section, we make reference to the study done by Hawkins et al. (2013). Although the inventory is mostly based on secondary data sources, it is perhaps (and to our knowledge) the most complete and transparent inventory of an EV that is currently publicly available.

Their research compares the environmental impact produced by driving 1 km in a conventional vehicle (diesel or gasoline) against an EV. It includes the modelling of a generic glider adapted to meet the specific configuration of each technology under study. Their inventory considers the production of the glider, drive train and the battery and comprises around 140 vehicle subcomponents.[13]

For the case of the EV, the researchers compared the impact of two different battery chemistries, namely Li-$FePO_4$ and Li-NCM, and analysed the use of three different energy mixes. The energy consumption during the use stage was estimated based on the NEDC driving cycle. Based on data from manufacturers, they assumed a consumption of 0.63 MJ/km for the EV and 68 ml/km and 53.5 ml/km for the gasoline and the diesel vehicle, respectively. For this study, the authors assumed a vehicle lifetime of 150,000 km.

The global warming potential (GWP) impact for each specific case was spread over the total life cycle and the results are shown in Fig. 27.8. In general, the largest contributor to the environmental impact of the six scenarios was found to be the use stage.

[12]For a comprehensive state of the research, we refer the reader to the literature reviews done by Hawkins et al. (2012) and Nordelöf et al. (2014).

[13]The complete LCI can be accessed online.

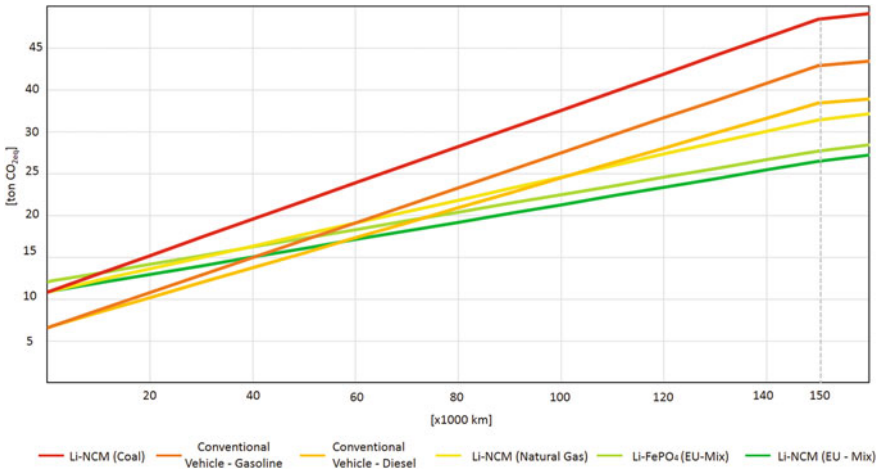


Fig. 27.8 Comparison of the life cycle GWP of a CV and an EV as function of the distance driven

For the case in which the European energy mix is used there is a general reduction in the life cycle CO_2-eq. emissions from EVs in comparison to the conventional ones. Under this condition, the difference on the GWP impact between the different battery cell chemistries is due only to the production stage. As seen in the figure, when EVs are powered with coal-based electricity, their life cycle CO_2-eq. emissions present increments of around 17–27% compared to gasoline and diesel, respectively.

The production stage also presents several interesting differences. The production of a conventionalvehicle was found to emit around half of the GHG emissions that are emitted during the production of an EV. The study reported that a GWP impact of around 13 tonne CO_2-eq. is produced during the production of an EV, 35–41% of which is caused by the production of the traction battery.[14] In addition, the cooling system required by the battery system is identified to contribute around 18% of the total CO_2-eq. from the production of an EV. Results for the other environmental impact categories are shown normalised to the scenario with the highest impact for each impact category in Fig. 27.9.

Several points are worth noticing from these results. First, the impact categories terrestrial acidification (TAP) and particulate matter formation (PMFP) behave very similarly in the EV and the conventional vehicle. As argued, the portion of hard coal and lignite used for the generation of the European electricity mix prevents the EVs to perform better than their conventional counterpart and therefore reduction in

[14]We refer the reader to the research done by Ellingsen et al. (2014) as it includes a very comprehensive LCI for a battery system similar to the battery in the study from Hawkins et al. (2013). As estimated by the author, for a lifetime of 150 000 km the battery reaches a GWP impact of approximately 4.7 tonnes CO_2-eq.

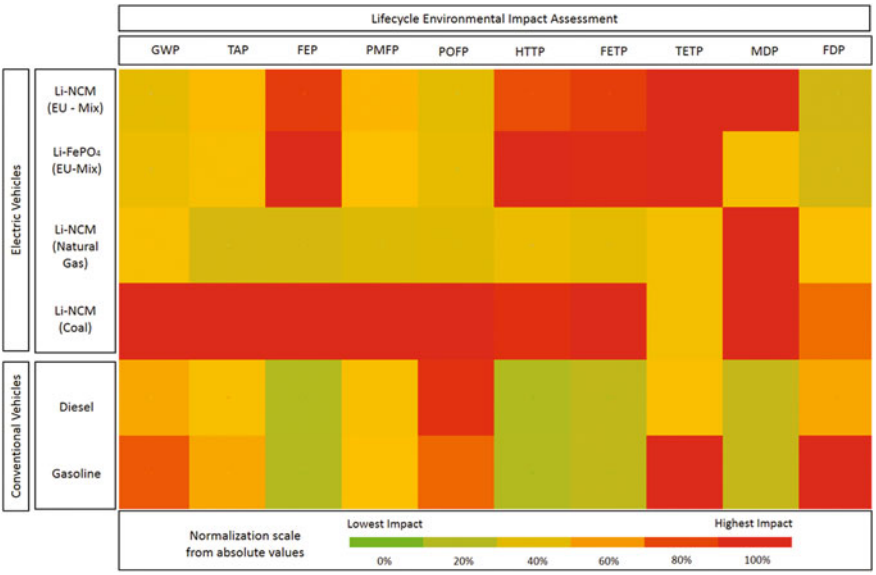


Fig. 27.9 Environmental impact of conventional and EV for different Impact Categories. Normalised from the absolute results

the life cycle TAP impacts can most probably be reached by powering EVs with electricity with lower sources of sulphur (e.g. natural gas).

As expected, the category photochemical oxidation formation (POFP) impact of EVs is significantly lower than for conventional vehicles as this impact is predominantly related to combustion processes. Human toxicity potential (HTP) is identified as a potential problem shifting by the authors. In this category, EV presents increments of up to 290% compared to CV which is mainly due to the increase in the use of metals like copper and nickel. These materials are usually produced through mining activities which are characterised by producing important amounts of toxic refuses. Finally, fossil resource depletion potential (FDP) potentially decreases if the EV is powered with average European electricity, but as shown, the advantages are not determinant if the coal-intensive energy mixes are used instead.

27.3.2 The Environmental Impact of a Lightweight Electric Vehicle

Using lightweight materials is one common strategy to reduce the weight of CVs. Lightweight materials used in CVs aim to reduce the energy consumption and thereby the environmental impact in the use stage of the vehicle. The savings in the

use stage have to outweigh the higher environmental impacts of the lightweight material in comparison to the reference material, which usually occur in the raw material acquisition, production and end-of-life stage.

In EVs, lightweight materials can have the same effect. Different parameters determine how lightweight electric vehicles perform in comparison to reference EVs and CVs and when and if a break-even is reached. For the comparison of electric vehicles—both lightweight and non-lightweight electric vehicles—with CV, regional and use stage specific parameters are relevant.

In both vehicle types, electricity or fuel is necessary to operate the air conditioning. However, in CV the excess heat from the engine is used to heat up the vehicle cabin. In EV, this is not possible because the electric motor is very efficient and generates almost no excess heat. Hence, heat has to be generated when needed, which requires the use of additional energy. Therefore, the ambient temperature has a strong influence on the energy demand of the EV and only a minor influence on the fuel consumption of the CV.

For the comparison of a lightweight EV with a reference EV, the electricity mix must be considered as well as material properties (e.g. the lightweight factor of the lightweight material in comparison to the reference material) and vehicle properties (e.g. the energy saving per kilometre for each reduced kilogramme). To cover all influencing parameters, the comparison of lightweight electric vehicles with CV and reference vehicles requires a systematic approach. First, a detailed system description of the vehicles and their use is necessary. Examples are the description of the daily and seasonal use pattern. Then, the modelling of the interdependencies of the parameters like: the energy mix, the ambient temperature, the use pattern and the properties of the lightweight materials is required.

Finally, an adequate visualisation of results simplifies the interpretation of results for both LCA and non-LCA experts. The visualisation of LCA results in form of a map is useful because the results of the comparative assertion of (lightweight) electric vehicles and conventional vehicles depend on the regional parameters electricity mix and ambient temperature.

Figure 27.10 shows the LCA world map of the comparison of a gasoline CV and an EV with a lithium iron-phosphate (Li-$FePO_4$) battery for the impact category climate change. The use pattern represents a commuter using the vehicle in the morning and the afternoon (daily use) evenly throughout the year (seasonal use). Blue and green colours indicate that the CV is advantageous. Red, orange and yellow colours indicate that the EV performs better than the CV. Due to the consideration of the ambient temperature, the results vary within one country. For some countries like Spain, Argentina or Mexico no clear decision for or against one vehicle type can be given.

When lightweight materials are used, the question arises if a break-even point x is reached during the lifetime of the vehicle. Do the savings in the use stage outweigh the higher environmental impact of the lightweight material in the production and end-of-life stage ($i_{P,lw}$ and $i_{E,lw}$) which exists in comparison to the environmental impact of the reference material ($i_{P,ref}$ and $i_{E,ref}$)? This also depends on the lightweight factor of the lightweight material in comparison the reference

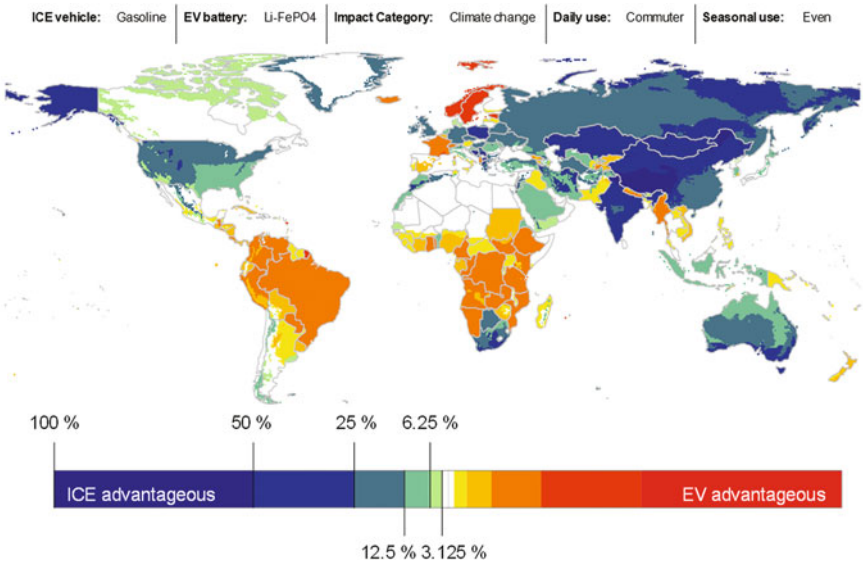


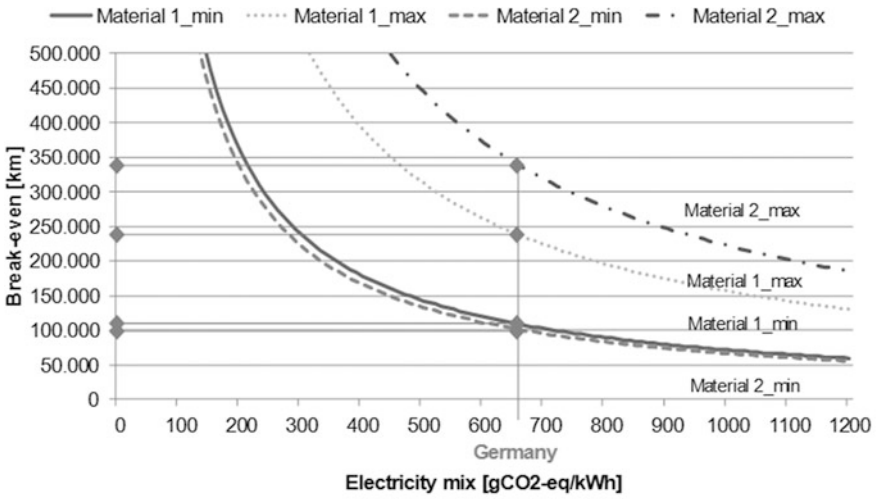
Fig. 27.10 LCA world map for the comparison of gasoline vehicle and electric vehicle with Li-$FePO_4$ battery for the impact category climate change, world map created with R and r world map. Taken from Egede (2016)

material (a_{lw}), the environmental impact of the electricity mix (i_e) and the saving in energy consumption of the vehicle per kilometre for each reduced kilogramme (c_{erv}). The following equation shows the calculation of this break-even point, X (distance driven in the vehicle):

$$x = \frac{a_{lw}(i_{P,lw} + i_{E,lw}) - (i_{P,ref} + i_{E,ref})}{c_{erv} * i_e(1 - a_{lw})} \tag{27.3}$$

Displaying the break-even point in relation to the energy mix leads to the chart in Fig. 27.11. The chart immediately allows to see when the use of a specific lightweight material leads to a break-even for a given specific energy mix, identified by its GHG emission intensity (the example of Germany in indicated in the figure). It is important to note that often ranges are given for the environmental impact of a material. This leads to ranges in the results for the break-even point. In the given example, the range of material 1 is more narrow than the range of material 2.

As a result, in Germany a break-even for material 1 is achieved for a total driving distance between 100,000 and 240,000 km whereas the break-even for material 2 is reached between 110,000 and 340,000 km. Further information on the environmental assessment of lightweight electric vehicles can be found in Egede (2016).



	Reference	Material 1_min	Material 1_max	Material 2_min	Material 2_max
$i_P + i_E$ (kgCO2-eq/kg)	2.38	2.7	2.9	2.8	3.3
α_M(-)	-	0.94	0.94	0.92	0.92
erv (Wh/km/kg)	0.0369				

Fig. 27.11 Break-even analysis of two different materials. Taken from Egede (2016)

27.4 Concluding Remarks and Perspectives

The move towards a sustainable private transportation is challenging. There are many different strategies being conceived to achieve reduction in energy consumption and production of GHG emissions in the sector specifically.

While it is true that the development and promotion of EVs could lead to cutting tailpipe GHG emissions, the actual environmental effect of such a measure needs a more comprehensive analysis. The LCA methodology, if applied transparently and unambiguously, offers the possibility of broadening the understanding of the consequences of a potential electrification of personal transportation.

To close this chapter, we address issues of concern related to the technological sector analysed and the application of the methodology for its evaluation. The lack of methodological harmony is a central issue in the discussion.

One of the largest challenges to overcome towards understanding the environmental implications of EVs is the high level of inconsistency among undergoing research. While the eLCAr guidelines aimed at harmonising the application of the LCA methodology to obtain more accurate information, much of the research available still fails to give a proper definition of the system being analysed and its scope.

Accordingly, benchmarking results among different studies reported in the literature is difficult due to aspects such as ambiguous setting of boundaries, variations in the product lifetime analysed and lack (or inexistence) of a functional equivalency to enable comparability between two or more vehicles analysed. In spite of the lack of consensus regarding the application the LCA methodology in this field, a common shared conclusion is that the source of the energy used to power the vehicle to a great extent defines its environmental impact. In other words, substantial improvements in several impact categories can be reached if EVs are powered with low impact energy sources and therefore, promoting the market penetration of EVs in regions where electricity comes mostly from fossil sources can mislead to an increase in the global GHG emissions from transportation.

The production stage of an EV is estimated to be up to two times more environmentally intensive than a CV. In particular, the battery system poses the biggest challenges. On the one side, current massively produced battery systems for mobility applications contain large amounts of metals whose mining processes are usually characterised by being very harmful on a local/regional level.

In this regard, the analysis of significant changes in the material supply chain of batteries is needed. Considering the recycling of battery systems and the potential recovery of materials is important as this is estimated to minimise local environmental impacts and reduce the overall energy use and emissions of its production (Dunn et al. 2015).

On the other side, there is a raising concern regarding the materials intended to be used for batteries. As these differ abruptly regarding their state of development, most of these materials are difficult to screen and evaluate from an environmental standpoint as their behaviour on an industrial scale (massively produced) might be unpredictable. A more detailed consideration of the vehicle's production, and especially of the battery system, within the application of the LCA is essential as this could lead to identifying potential problem shifting issues.

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Author Biographies

Felipe Cerdas mechanical and environmental engineer involved in the application of the LCA in industry since 2009. His work has been focused on the lifecycle environmental and economic assessment of energy storage systems for electric vehicles. Interested in the application of LCA for the assessment of emerging technologies in early stages.

Patricia Egede focus on the LCA of electric vehicles, particularly in fleet operations or with lightweight materials. Main interest in the differences of environmental impacts related to regional influencing factors and resulting visualization challenges, member of the European eLCAr project to adapt ILCD Handbook to electric vehicles.

Christoph Herrmann has led national and international research projects in the context of sustainable manufacturing and life cycle engineering since 1997. Main interest is the further development of LCA as an engineering tool that drives innovation.